Urban Heat Island (UHI) and Urban Cooling Island (UCI) Effects: How They Related?

Menglin S. Jin[1,*] and Hengyu Zhang[2]

[1]Department of Atmospheric and Oceanic Science, University of Maryland, College Park

[2] SpringGem Weather Information, LLC

Background

Urban heat island effect (UHI) is traditionally detected, by using a pair of weather stations, that urban 2-m air temperature is higher than rural region by 0.5-1 °C. From satellite-observed skin temperature data, UHI is found more significant during both daytime and nighttime (Jin et al. 2005). On the contrary, urban cooling island effect (UCI) has occasionally reported from the ground observations.

How are UHI and UCI related? Are they both true?

In this study, UHI for inner land regions was investigated using satellite data, ground observations, and simulations with an Single-Layer Urban Canopy Parameterization (SLUCP) coupled into the regional Weather Research Forecasting model (WRF, http://wrf-model.org/index.php). Specifically, using the satellite-observed surface skin temperatures (T_{skin}), the intensity of UHI was first compared for two inland cities (Xi'an City, China and Oklahoma City (OKC)), which have different city populations and building densities. The larger population density and larger building density in Xi'an lead to a stronger skin-level UHI effect by 2 °C. However, the ground observed 2-m surface air temperature (Tair) observations showed an urban cooling island (UCI) effect over the downtown region in OKC during the daytime of July 19, 2003, from a DOE field campaign (Joint Urban 2003). To understand this contrast between satellite-based Tskin and ground-based Tair, a sensitivity study using WRF/SLUCP was analyzed. The model reproduced a UCI effect in OKC. Furthermore, WRF/Noah/SLUCM simulations were also compared with the Joint Urban 2003 ground observations, including wind speeds and directions.

JU2003 Field Experiments Results

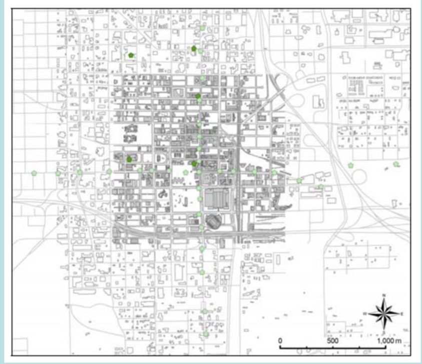


Figure 1: (a) Overview of the PNNL Meteorological Station and HOBO locations. The light green pentagons are HOBOs, while the dark green pentagons are meteorological statio Ns ©Courtesy of Battelle memoria l Institute.

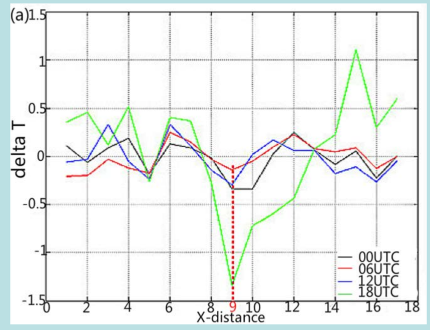
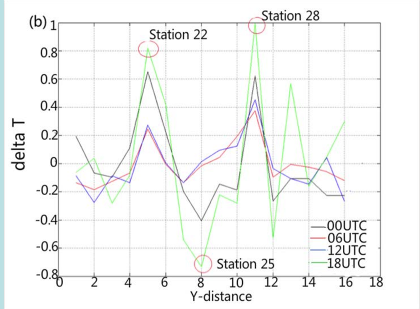


Figure 2: The temperature difference (e.g., Delta T, unit in °C) values for 2-meter air temperatures for each station in (a) X-direction and (b) Y-direction.



UCI is suggested by comparing the most central building regions sites 8 and 9 and other stations. The shadow of tall buildings at sites 8 and 9 made the 2-m T_{air} lower than other regions

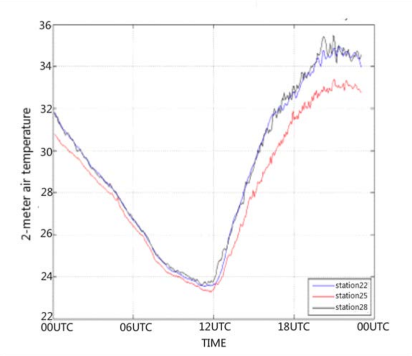


Figure 3: Twenty-four hourly diurnal variation of 2-meter air temperatures (unit in °C) from PNNL HOBO station No. 22, station No. 25, and station No. 28.

A Joint Urban 2003 Field Campaign The Joint Urban 2003 (JU2003) field campaign, sponsored by the U.S. Department of Defense, Defense Threat Reduction Agency, and the U.S. Department of Homeland Security, was conducted in Oklahoma City (OKC), Oklahoma from 28 June to 31 July 2003.

Over 150 scientists and engineers as well as many foreign institutions participated in this project aiming to investigate the atmospheric dispersion in OKC. Air temperature sensors, radiosondes, radars, lidars, sodars, and sonic anemometers were deployed as a part of this initiative, and the physical processes—including surface energy balance in the urban area.

Satellite-based Remote Sensing Observed UHI

Using MODIS skin temperature and land cover data, UHI is very clearly identified for Oklahoma and Xian, China.

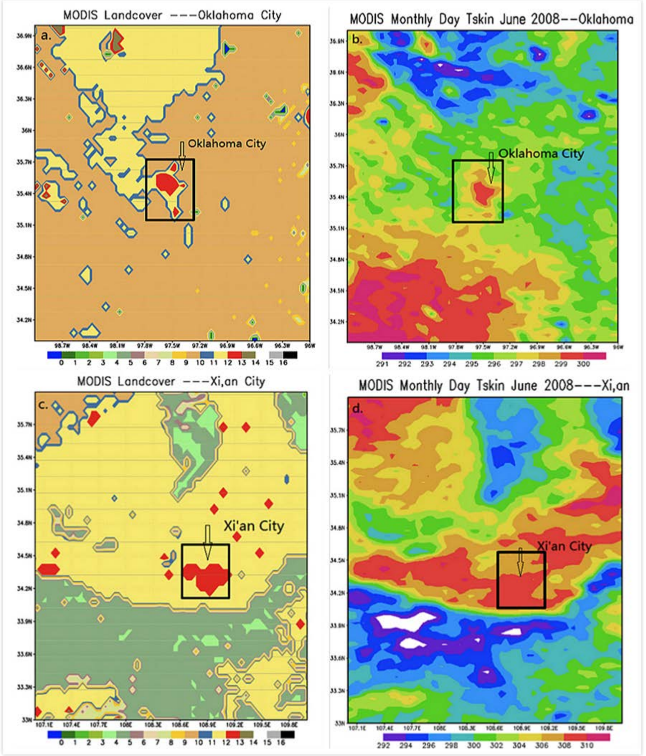


Figure 4: MODIS land surface cover type of (a) Oklahoma and (c) Xi'an. MODIS classifies the land cover to 17 differing classifications:.(1) Evergreen Needleleaf Forest, (2) Evergreen Broadleaf Forest, (3) Deciduous Needleleaf Forest, (4) Deciduous Broadleaf Forest, (5) Mixed Forest, (6) Closed Shrubland, (7) Open Shrubland, (8) Woody Savannas, (9) Savannas, (10) Grassland, (11) Permanent Wetland, (12) Cropland, (13) Urban and Built-up, (14). Cropland/Natural Vegetation Mosaic, (15) Snow and Ice, (16) Barren or Sparsely Vegetated. Urban area is the red color in the mapped areas. Locations of OKC and Xi'an City are marked in the figures. MODIS monthly daytime land surface temperature (unit in K) was recorded in June 2008 by Terra at 10:30 local time for (b) OKC in June 2008 and (d) Xi'an City.

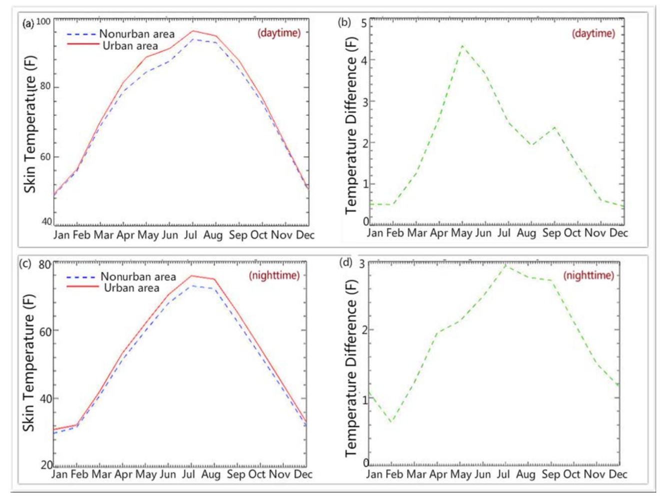


Figure 5: (a) OKC monthly averaged daytime skin temperature (2001-2008), (b) OKC monthly averaged daytime skin temperature difference (urban − nonurban), (c) OKC monthly averaged nighttime skin temperature (2001-2008), (d) OKC monthly averaged nighttime skin temperature difference (urban − nonurban). Temperature unit in K.

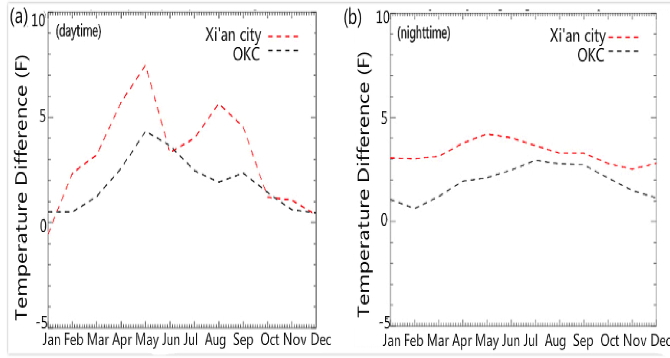


Figure 6: (a) Xi'an City and OKC monthly averaged daytime skin temperature difference (urban − nonurban), (b) Xi'an City and OKC monthly averaged nighttime skin temperature difference (urban −nonurban). Temperature unit in K.

WRF/SLUCM Simulation

The Urban Canopy Model (UCM) is a single layer model coupled to the WRF model which includes a 2-D street canyon.

A 24-h simulation of WRF/Noah began at 1200 UTC (0600 LST) on July 19, 2003, with the boundary conditions from NCEP North American Regional Reanalysis (NARR). The horizontal domain created for this simulation was comprised of three nested domains with a grid spacing of 25 km, 5 km, and 1 km.

Two simulations were performed: a control run without SLUCM and a sensitivity run with SLUCM.

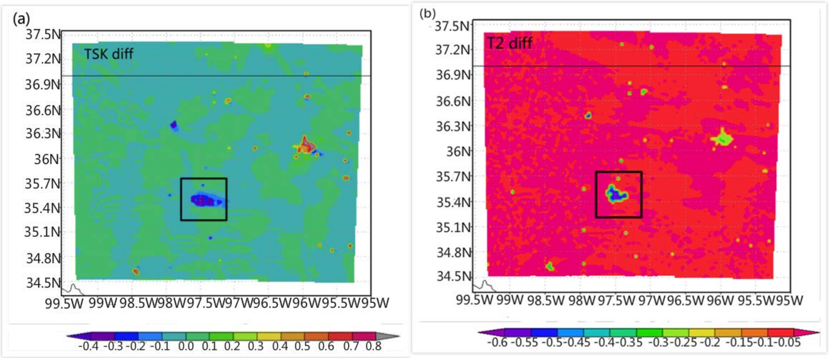


Figure 7: (a) WRF simulated surface temperature difference at 18 UTC, July 19, 2003, in OKC for T_{skin} difference (sensitive run – control run). **(b)** WRF simulated surface temperature difference at 18 UTC, July 19, 2003 in OKC for 2-meter T_{air} difference (sensitive run – control run) temperatures (unit in K), and OKC is represented as the rectangle area.

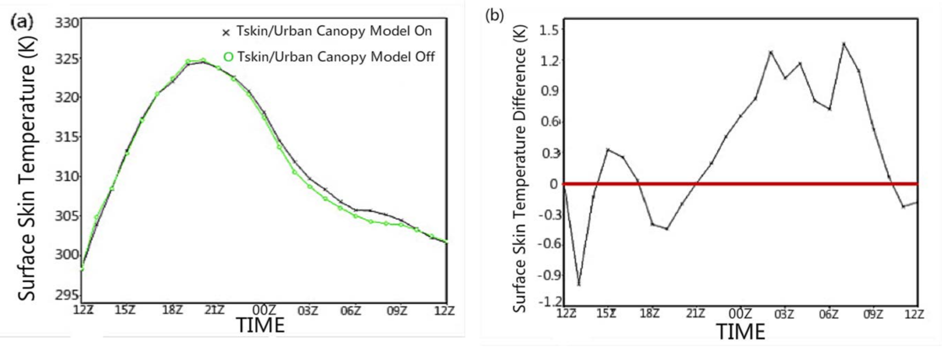


Figure 8: (a) WRF model simulated skin temperature (Tskin) for the sensitive run and control run in urban regions in OKC. The green curve is for the control run (i.e., Tskin with urban canopy model off in WRF simulation), and the black curve is for the simulation of the sensitive run (i.e., Tskin with urban canopy model turned on in WRF simulation). (b) Skin temperature difference between the sensitive run and control run (sensitive run minus control run) in urban regions in OKC. Temperature difference are in unit K.

The 24-h simulation of T_{skin} began at 1200 UTC, July 19, 2003 and pertains to both the sensitive run and the control run (Fig. 8a). The peak value of T_{skin} for the sensitive run is 324.80 K at 19 UTC, and the minimum value is 298.50 K at 12 UTC. On the other hand, for the control run, the peak value of 324.95 K is obtained also at 19 UTC, and the minimum value of 298.50 K is measured at 12 UTC. The peak value of both runs occur at 19 UTC because the incoming solar radiation is the strongest at noon (18 UTC) and, as the surface is heated, T_{skin} starts increasing. Thus, T_{skin} reaches the peak value at 19 UTC. The T_{skin} difference between the sensitive run and the control run (Fig. 8b) indicates that, <u>during most of the daytime, the T_{skin} simulated from the sensitive run are lower than the T_{skin} simulated from the control run</u>.

Acknowledgements:
This work was partly supported by NSF Large-scale Dynamics Program (Grant number 0855480) and partly supported by NASA Precipitation Program (Grant number NNX13AG99G and NX16AD87G).

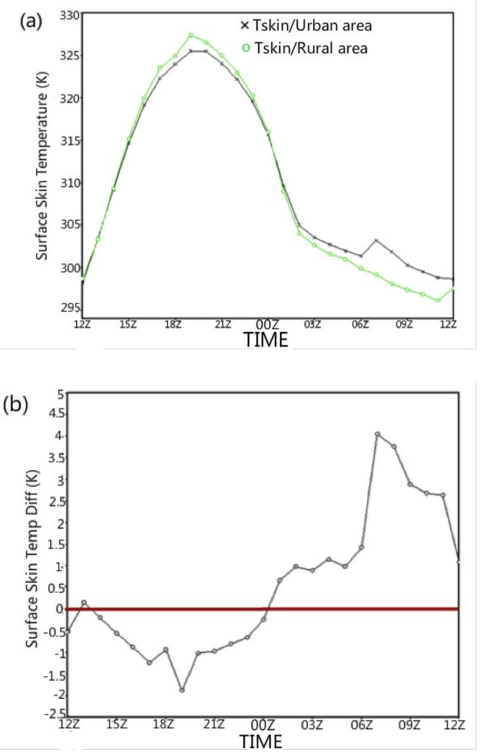


Figure 9: (a) the WRF/SLUCM -simulated T_{skin} (urban vs. rural) in OKC, with the green curve representing the T_{skin} over OKC urban area, and the black curve representing the T_{skin} over its rural area. **(b)** the SLUCM-simulated T_{skin} difference (urban − rural) in OKC. Temperature difference is in unit K.

The 24-h WRF/SLUCM simulation of T_{skin} for both the urban area and rural area (Fig. 9a) and the T_{skin} difference between urban area and rural area (Fig. 9b) in OKC suggest that, during most of the daytime, the T_{skin} measurements over the urban regions are lower than those observed over the rural regions in OKC, by about 2 K. The peak value of Tskin (325.80 K) over urban regions in OKC was measured at 19 UTC, while the minimum T_{skin} (298.0 K) occurred at 12 UTC. However, for the Tskin over the rural regions in OKC, the peak of about 327.8 K occurred at 19 UTC, and its minimum of about 296.5 K was measured at 11 UTC. <u>This simulated result is consistent with the UCI effect yielded by the ground observations. Namely, UCI occurs during the sunny daytime because of the building shadow effect, but UCI cannot offset UHI at nighttime, and thus a UHI signal is observed at the daily averaged scale.</u>

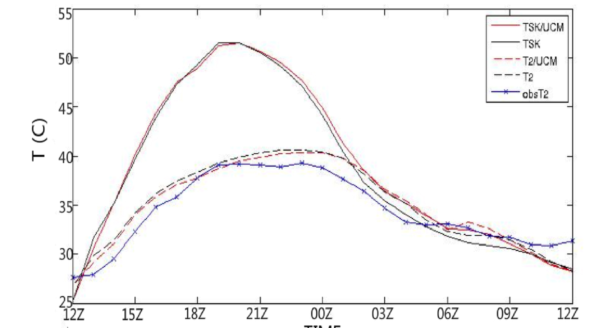


Figure 10: Comparison of WRF-simulated skin temperature (TSK in legend) and 2-m air temperature (e.g., T2) with the ground-observed air temperature (e.g., obs T2). The red solid line represents the model-simulated skin temperature with SLUCM turned on (e.g., the sensitive run), the black solid line represents the model-simulated skin temperature without SLUCM turned on (e.g., the control run), the red dashed line shows the model-simulated 2-m air temperature with SLUCM, the black dashed line shows the model-simulated 2-m air temperature without SLUCM, and the blue line represents the ground-observed air-temperature from PNNL HOBO station 9. Temperature is in unit °.

Conclusions:

1. An urban area is a highly heterogeneous environment and different cities have different types of urban sub-surfaces, geometric conditions, and population densities. As a result, the UHI effect differs between cities such as OKC and Xi'an, although both are inland cities at the same latitude.
2. There are competing factors and physical processes in urban surface layer that lead to UHI or UCI both possible. Specifically, building shadow cools the surafce under the sunny time. This is a competing effect than the less soil moisture and less vegetation coverage in urban regions, and thus during daytime, it is possible for a cooling surface, in particular, over the tall building areas.
3. Skin temperature and 2-m air temperature fields may have different UHI or UCI signals. The satellite observed skin temperature in OKC, which showed an evident UHI effect, was monthly averaged. The ground observation of 2-m air temperature and modeled surface skin and air temperatures, which suggested an UCI effect but only during daytime and at hourly resolution.

Jin, M. and R. E. Dickinson, 2010: Land Surface Skin Temperature Climatology: Benefitting from the Strengths of Satellite Observations. Environmental Research letters, 5 044004.
Zhang, H. M. Jin, M. Leach, 2017: A Study of the Oklahoma City Urban Heat Island Effect Using a WRF/Single-Layer Urban Canopy Model, a Joint Urban 2003 Field Campaign, and MODIS Satellite Observations. Climate 2017, 5(3), 72; doi:10.3390/cli5030072.